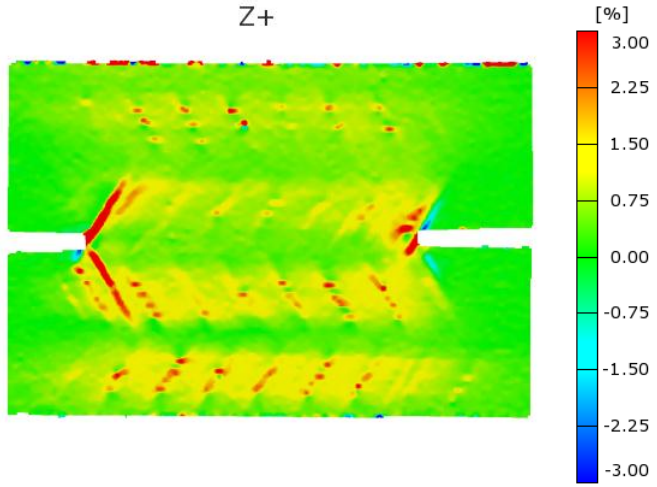
Full-field Deformation Measurement Techniques for a Rotating Composite Shaft

Lee W. Kohlman[1], Charles R. Ruggeri[1], Richard E. Martin[2], Gary D. Roberts[1], Robert F. Handschuh[1]

[1]NASA Glenn Research Center
[2]Cleveland State University

Motivation

- NASA Rotary Wing project is investigating multispeed drive system concepts. Weight reduction of components could be achieved through the use of composite materials.
- Fatigue failure of composite parts is related to local damage
- Local composite material failure can be resolved by static Digital Image Correlation (DIC).



Strain field of a notched composite coupon
(Measured by digital image correlation)

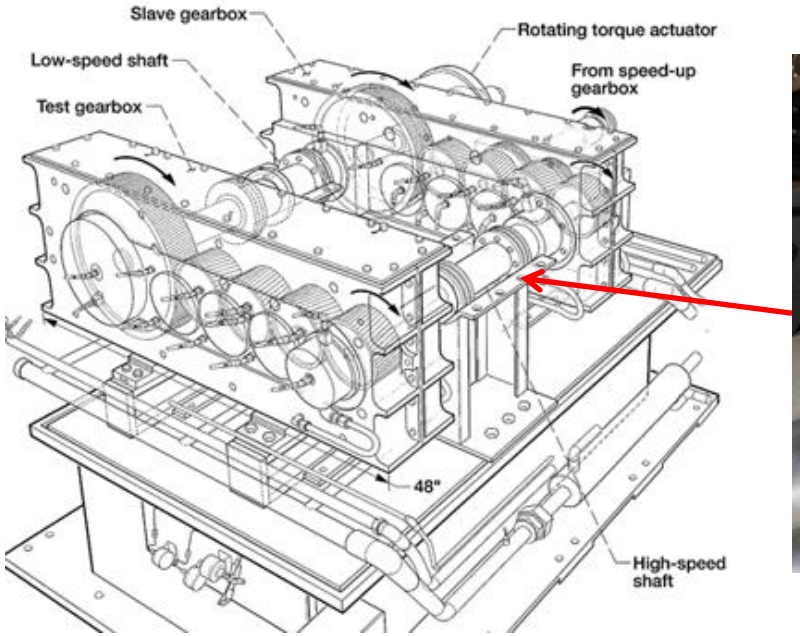
Example composite flexible shaft element

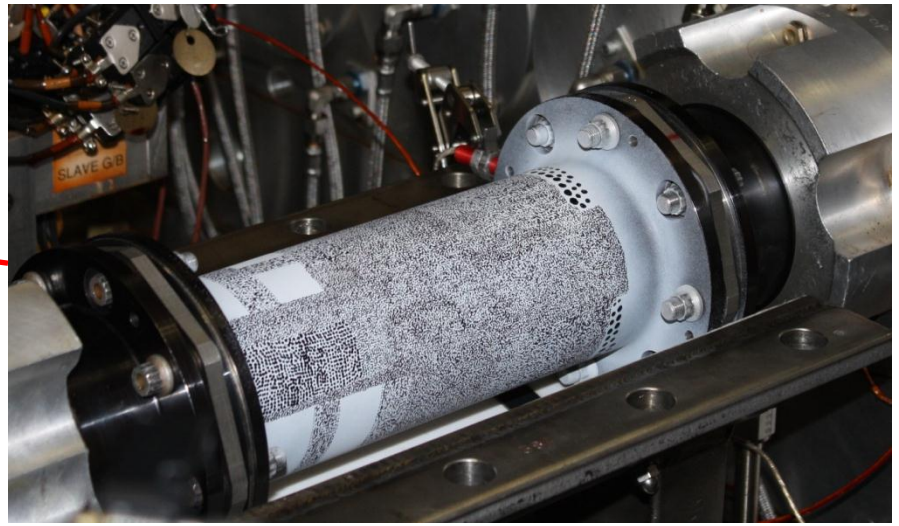
Test Goals

- Evaluate current capabilities of DIC for use on high speed rotating components
- Identify areas where improvements are needed
- Identify Non-Destructive Evaluation methods that are the most useful for observing and tracking the progression of damage in the composite material

Available Gear Test Rig: High Speed Shaft

- Normal maximum operating conditions
  - 15,000 rpm @ 20,000 in-lbs (4760 HP)
- Maximum conditions with composite test article and high speed shaft shroud removed
  - 5,000 rpm @ 10,000 in-lbs (793 HP)
- Shaft length = 10 inch; Shaft diameter = 3.5 inch

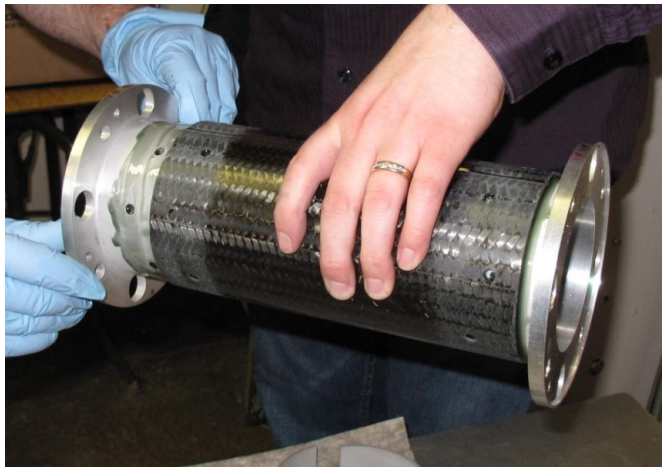


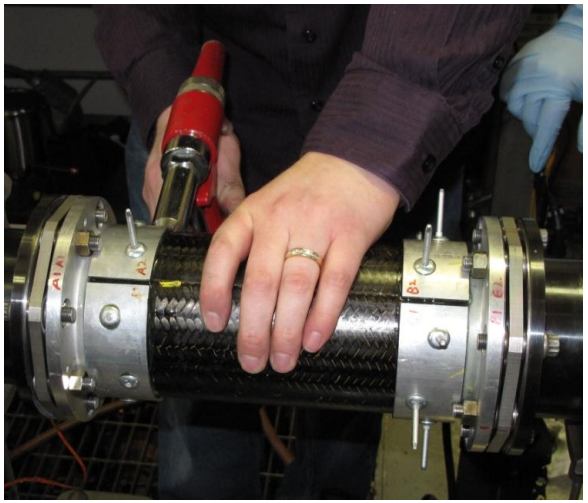


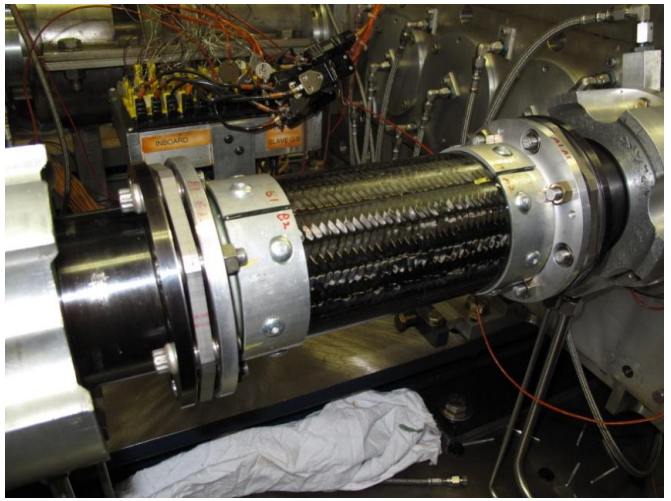
Original steel shaft with DIC pattern

Composite Test Article Fabrication

- Carbon/epoxy triaxial over-braided tube
  - Toray T700s carbon fiber and Cytec 5208 epoxy
  - 6 ply quasi-isotropic architecture
  - ~4 in diameter with 1/8th inch wall thickness
- 6061 aluminum end flanges and split ring
- Hysol EA 9693 adhesive
- High strength steel rivets







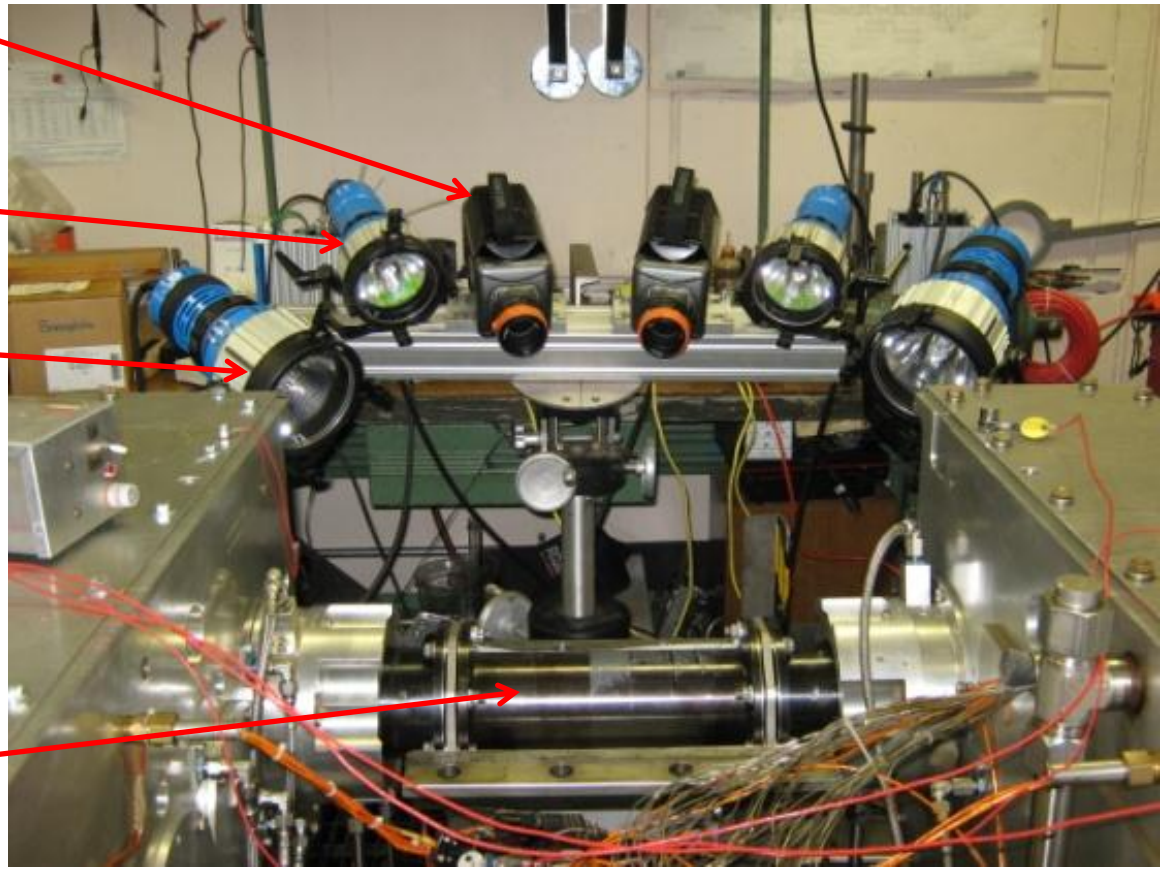
High Speed Digital Image Correlation

Phantom V10 Cameras

200 Watt HMI Lights

400 Watt HMI Lights

High Speed Shaft (original steel component)

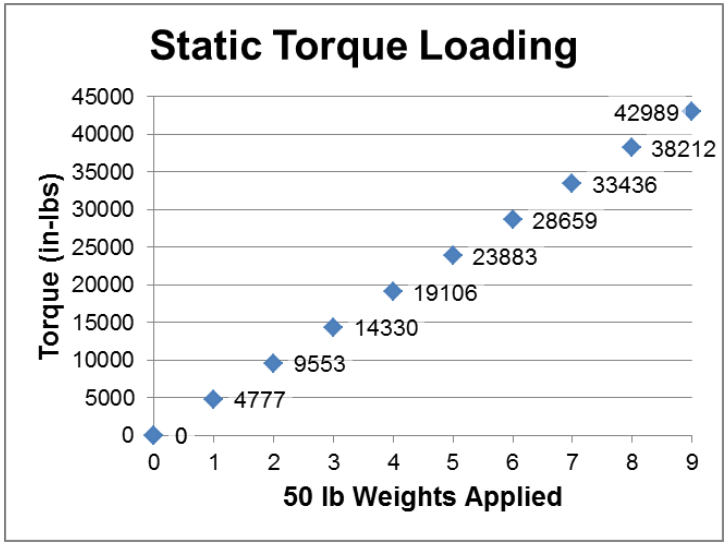


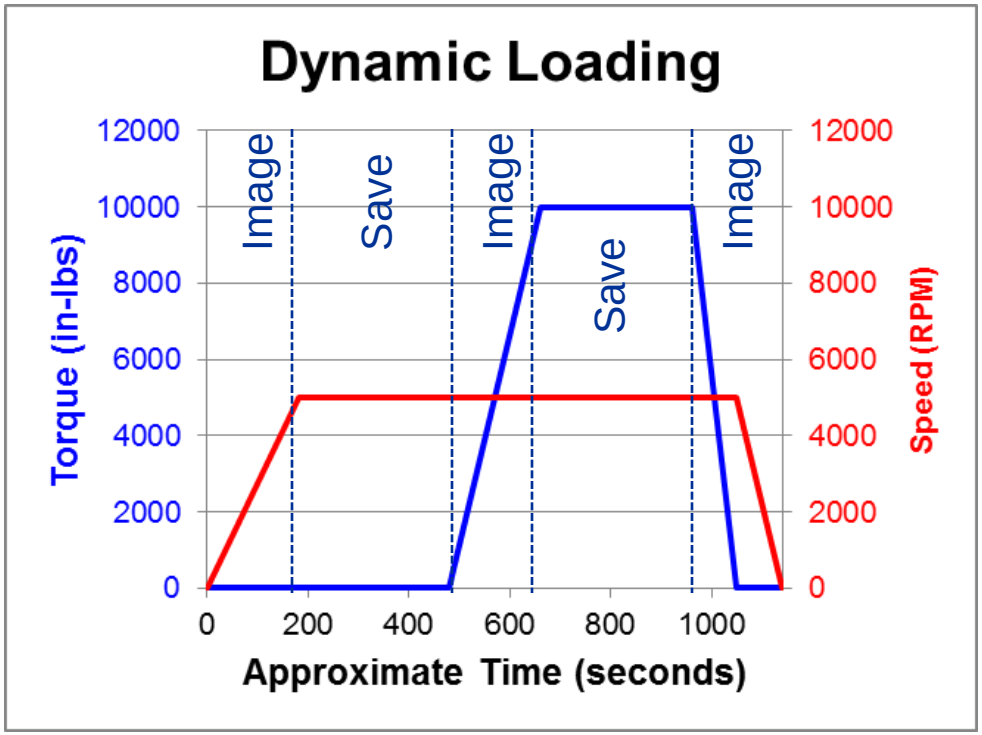
Example DIC Pattern

Test Plan

- Dynamic Tests
  - Steel Shaft (for setup)
  - Undamaged Composite
  - Impact Damaged Composite
- Static Test
  - Impact Damaged Composite Load to Failure

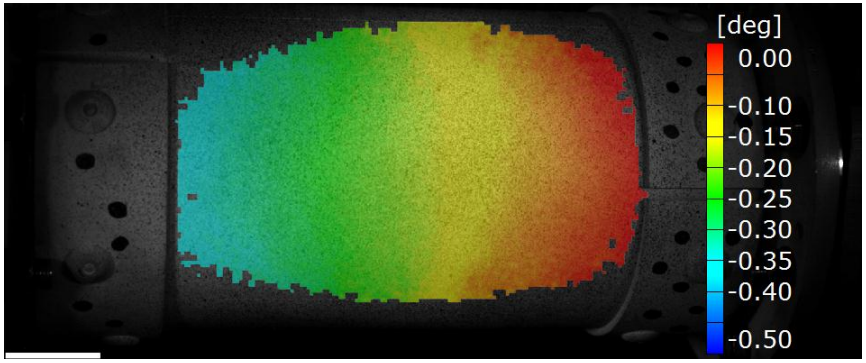
- Data Collection Methods
  - Digital Image Correlation
  - X-ray CT
  - Acoustic Emission
  - Thermography





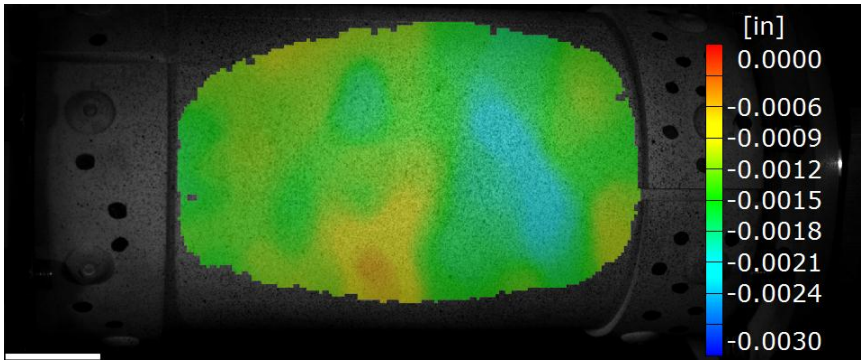
DIC Results: Dynamic, Undamaged @ Max Torque (10,000 in-lbs)

min -0.5° max 0°



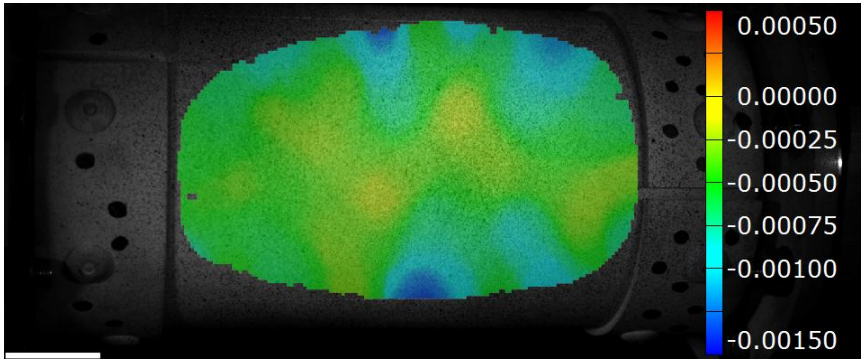
Twist Angle (deg.)

Range: -0.003 to 0 inches



Radial Displacement (in.)

Range: -0.0015 to 0.0005



Shear (ε_{xy})

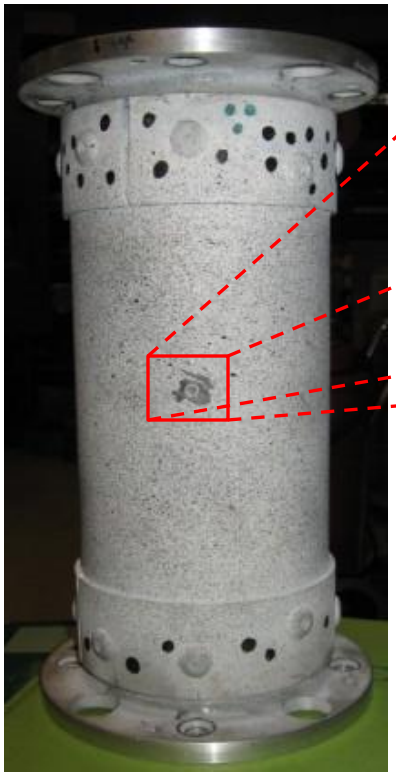
Impact Damage

Videos of Impacts
(recorded at 25,000 fps, played at 25 fps)

423 ft/sec

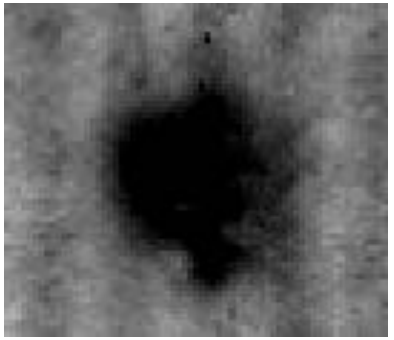
410 ft/sec

Two low speed impacts were performed using a ¼” steel ball bearing to induce delamination in the composite tube.



Impacted Test Article

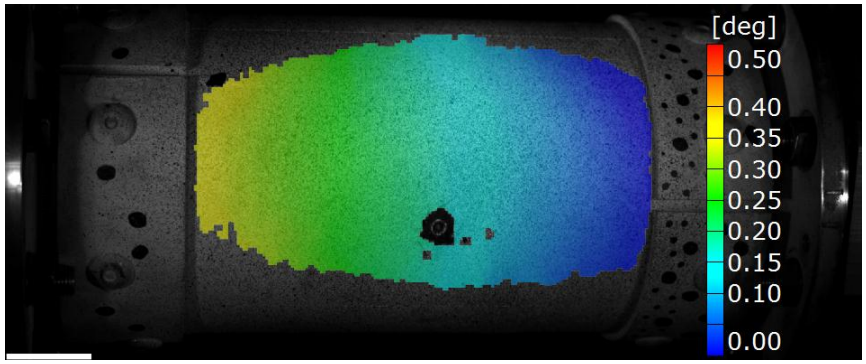
Image of Damage



Thermography of Damage

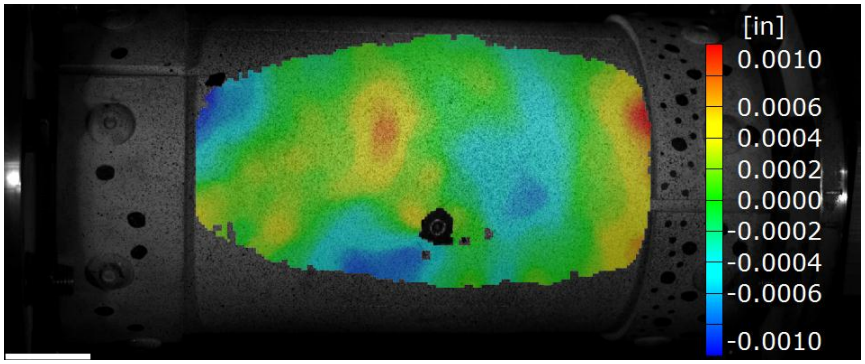
DIC Results: Dynamic, Damaged @ Max Torque (10,000 in-lbs)

max 0.5° min 0°



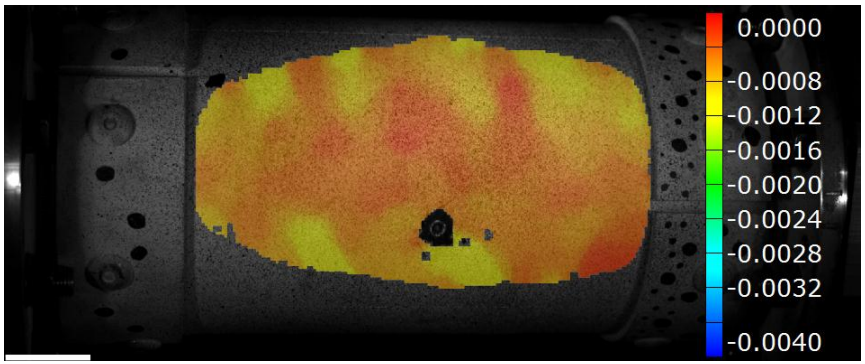
Twist Angle (deg.)

Range: -0.001 to 0.001 inches



Radial Displacement (in.)

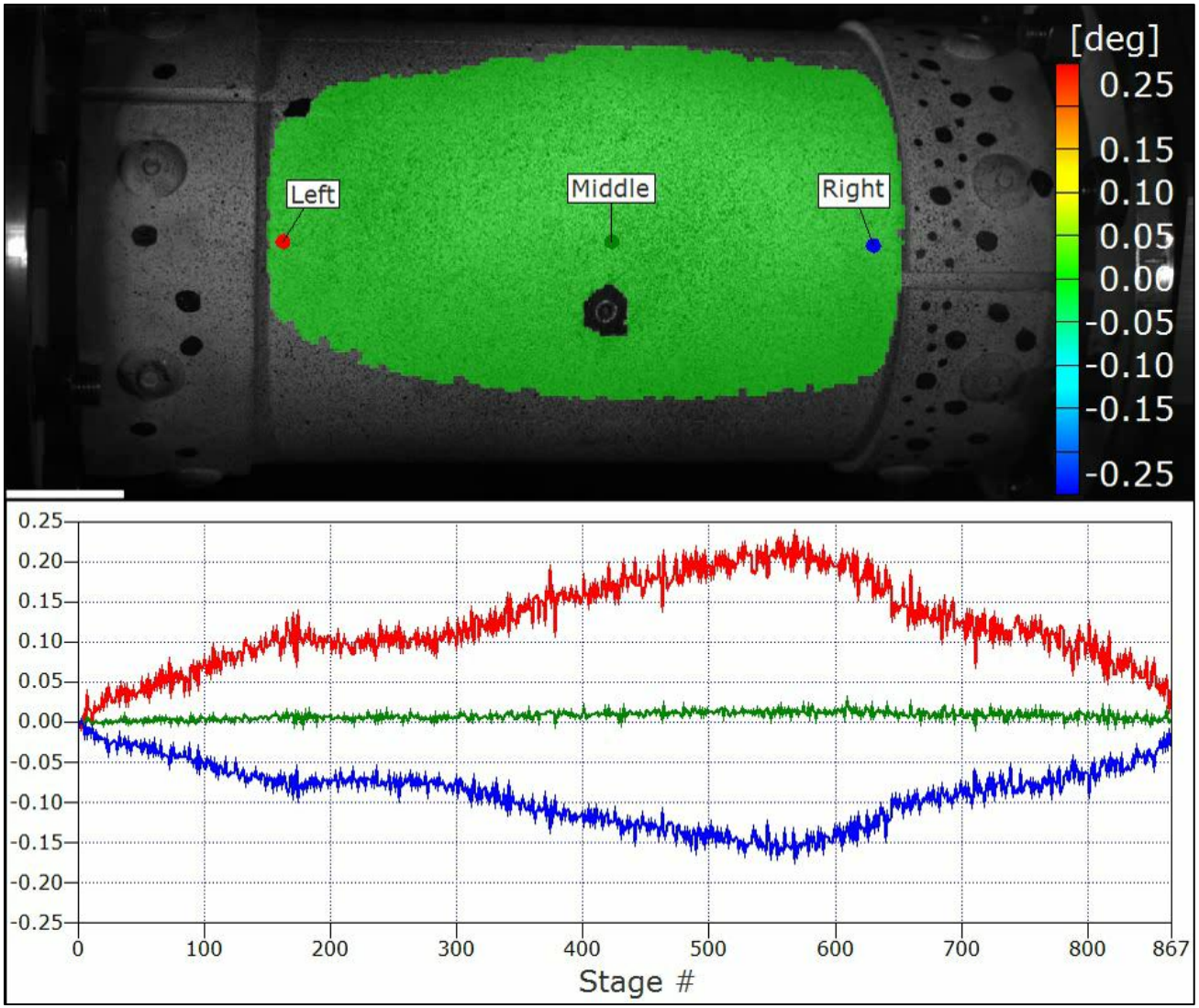
Range: -0.004 to 0.0000



Shear (ε_{xy})

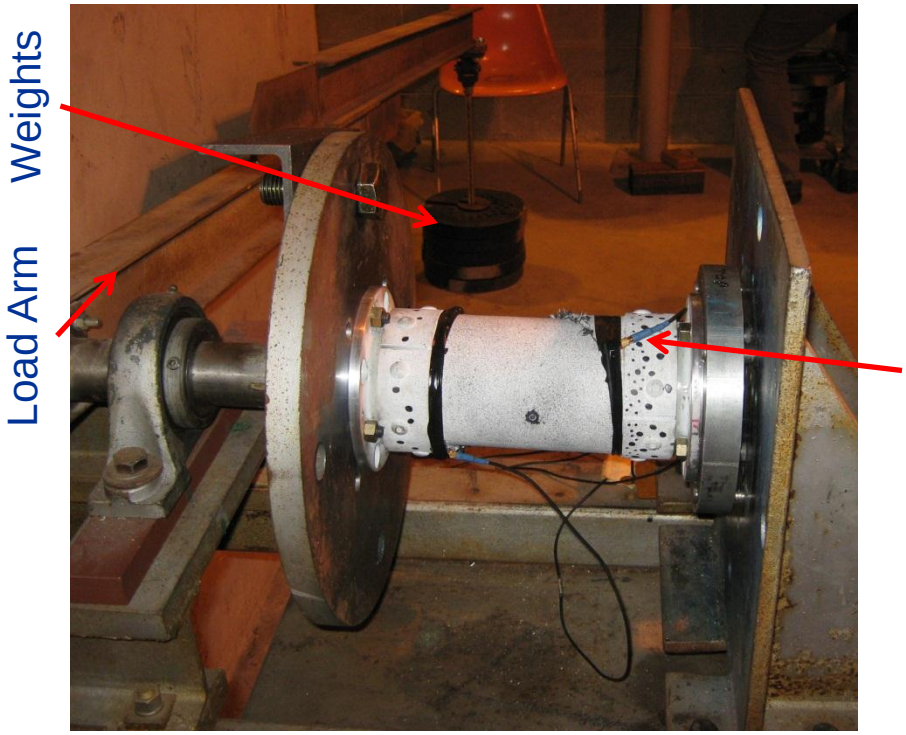
DIC Results: Dynamic, Damaged Twist Angle

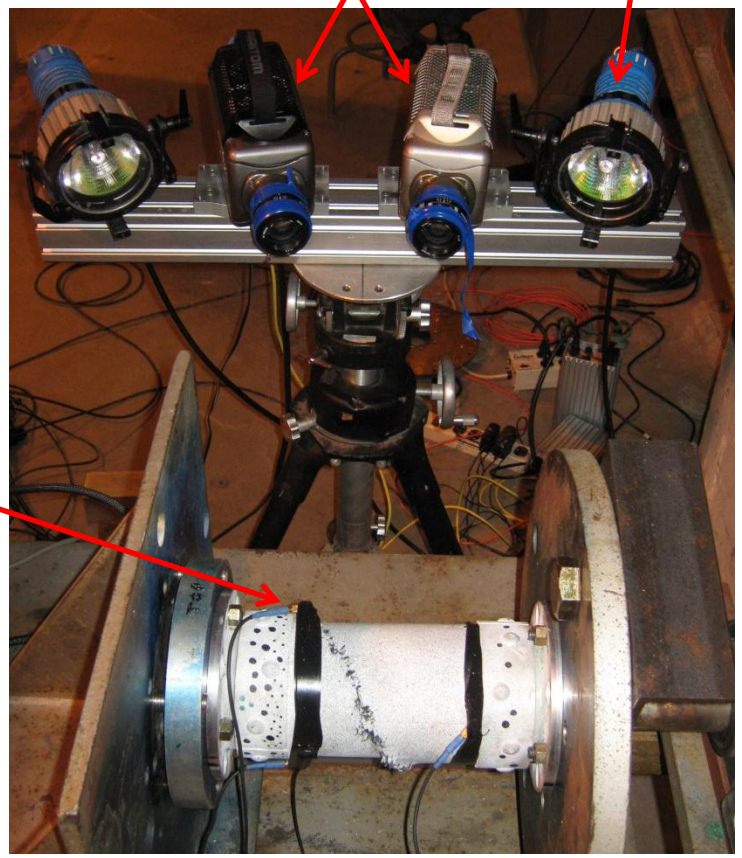
- Speed up to 5000 RPM
- Hold
- Increase torque to 10,000 in-lbs
- Reduce torque
- Slow down



Static Torque Test to Failure

- 50 lb weights were added to the loading arm
- DIC and Acoustic Emission were used during loading



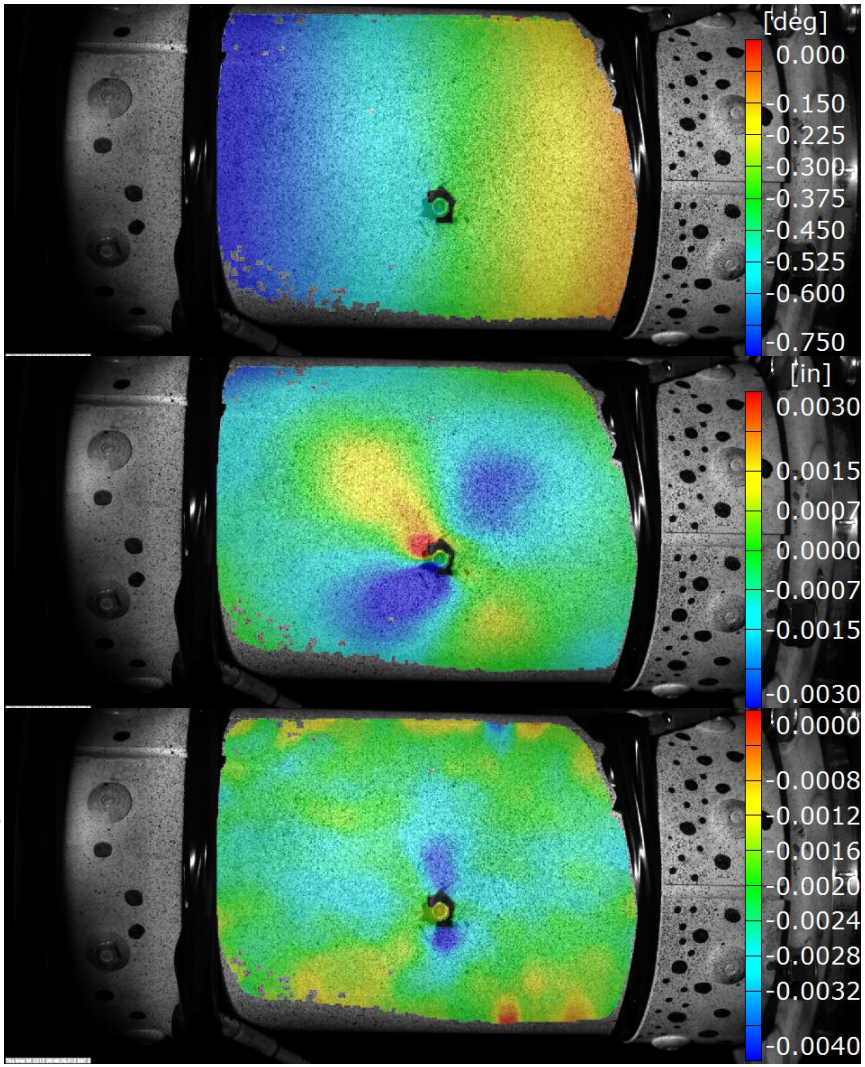


DIC Results: Static, Damaged @ Max Torque (~38,000 in-lbs)

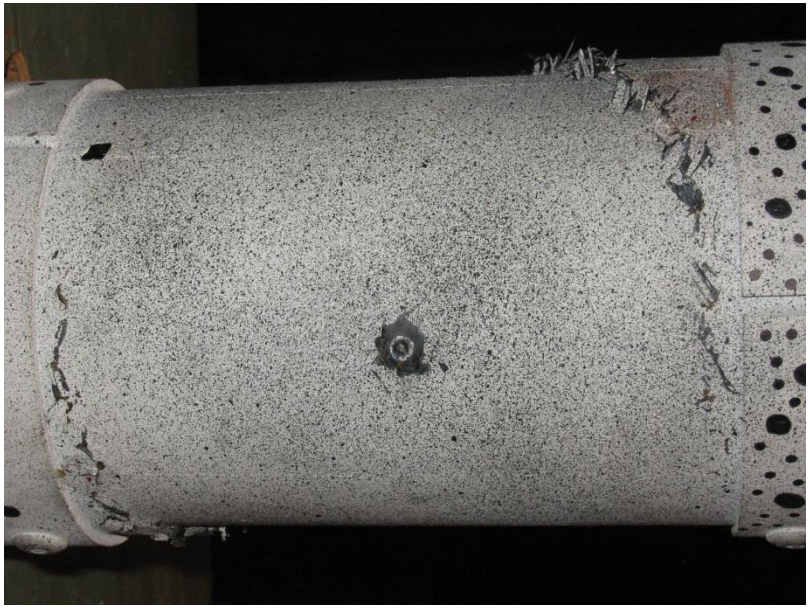
Twist Angle (deg.)

Radial Displacement (in.)

Shear (ε_{xy})

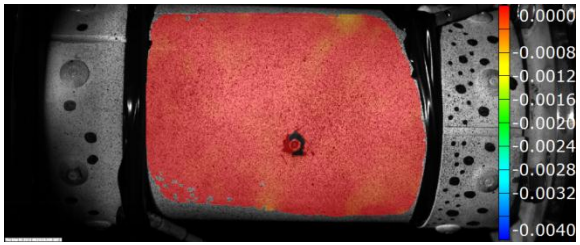


Failure Image

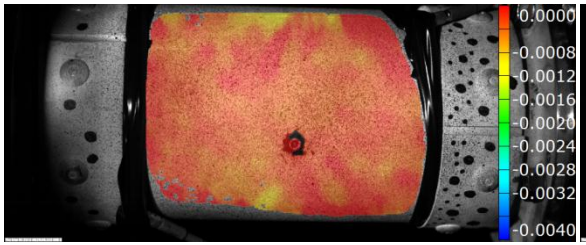


The tube failure initiated at the impact damage location on the back of the tube.

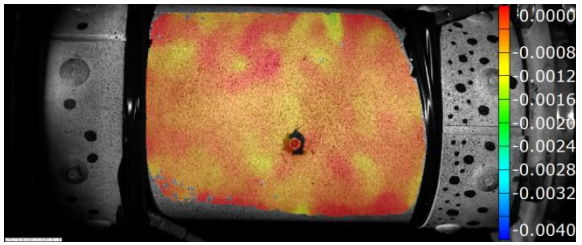
DIC Results: Static, Damaged Shear Strain (ε_{xy})



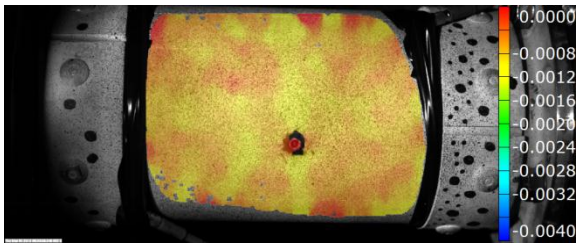
0 in-lbs



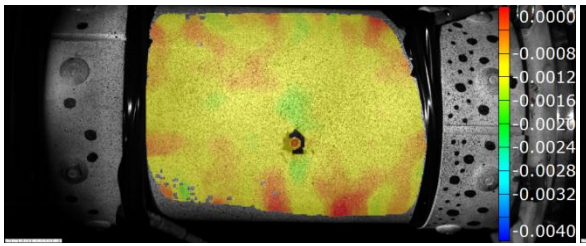
4777 in-lbs



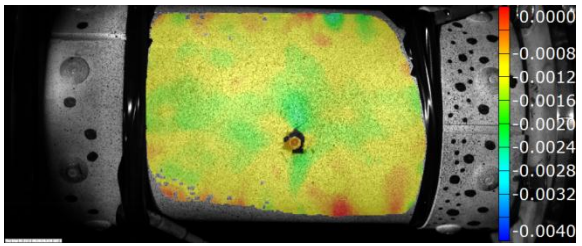
9553 in-lbs



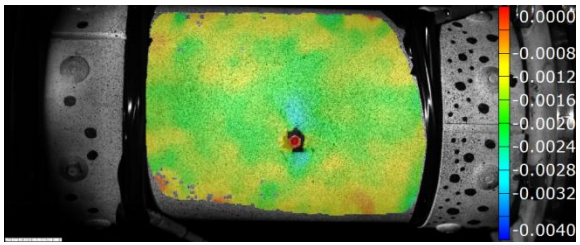
14330 in-lbs



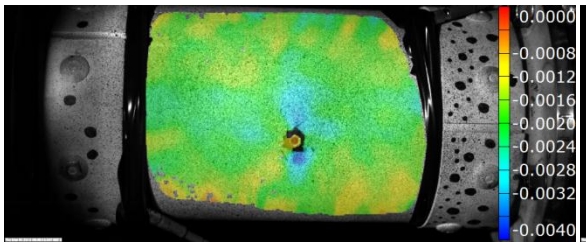
19106 in-lbs



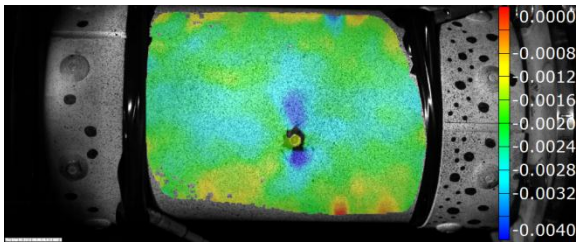
23883 in-lbs



28659 in-lbs

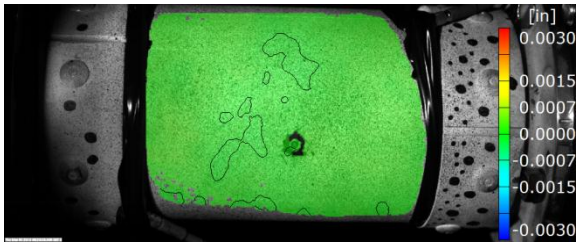


33436 in-lbs

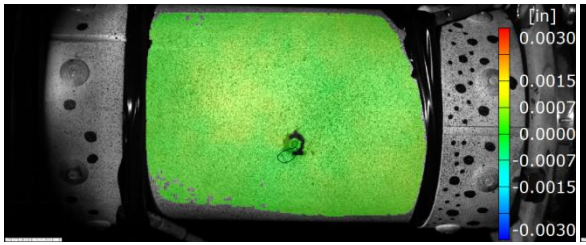


38212 in-lbs

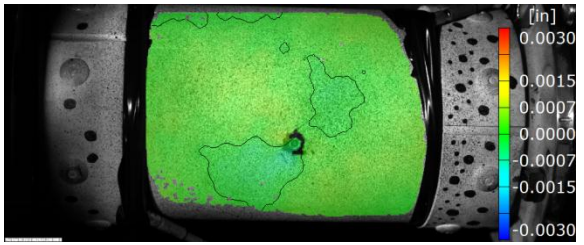
DIC Results: Static, Damaged Radial Displacement (in.)



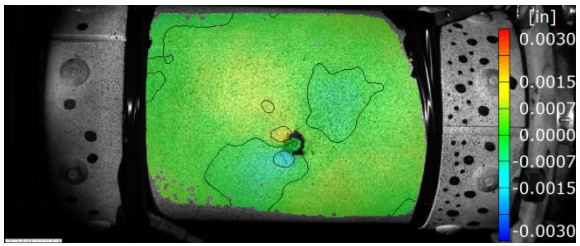
0 in-lbs



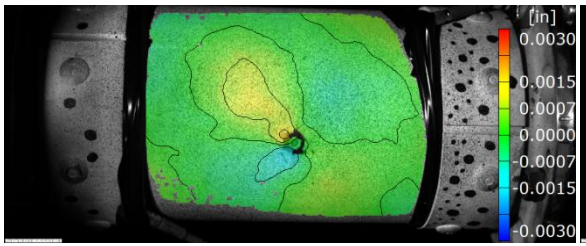
4777 in-lbs



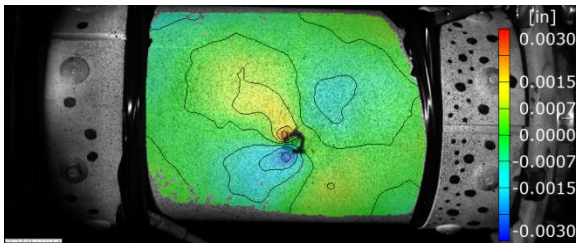
9553 in-lbs



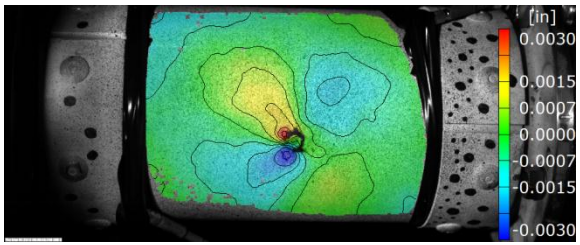
14330 in-lbs



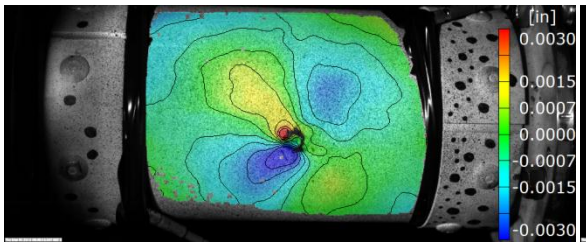
19106 in-lbs



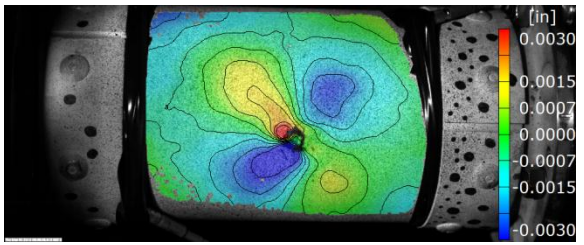
23883 in-lbs



28659 in-lbs



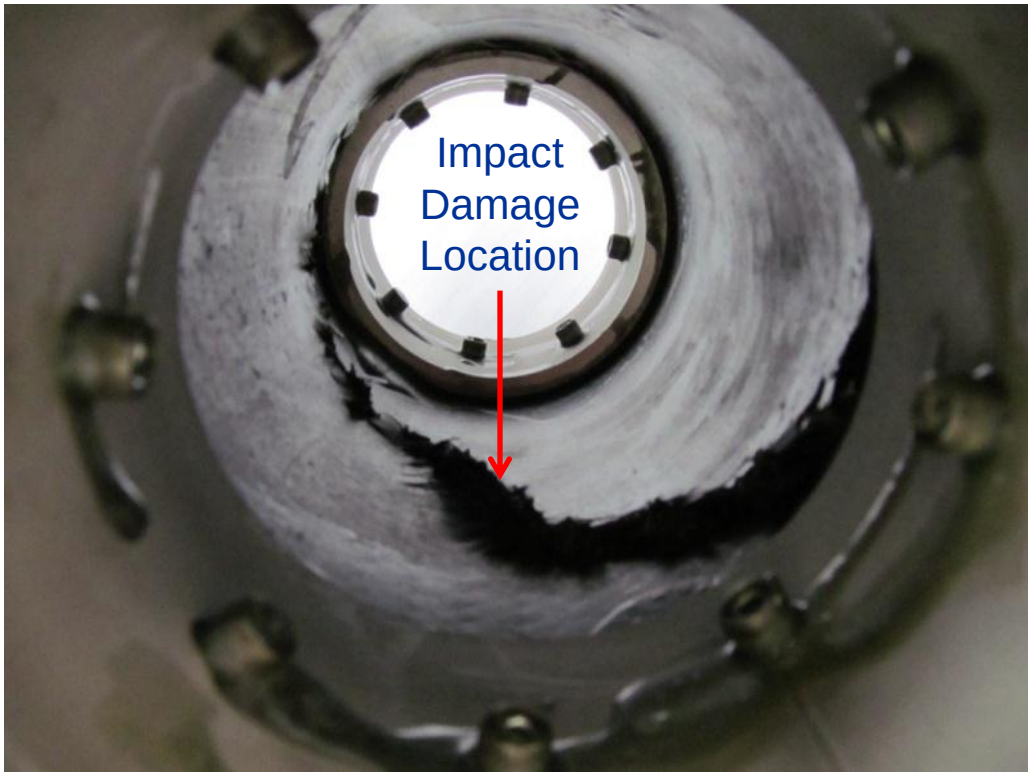
33436 in-lbs



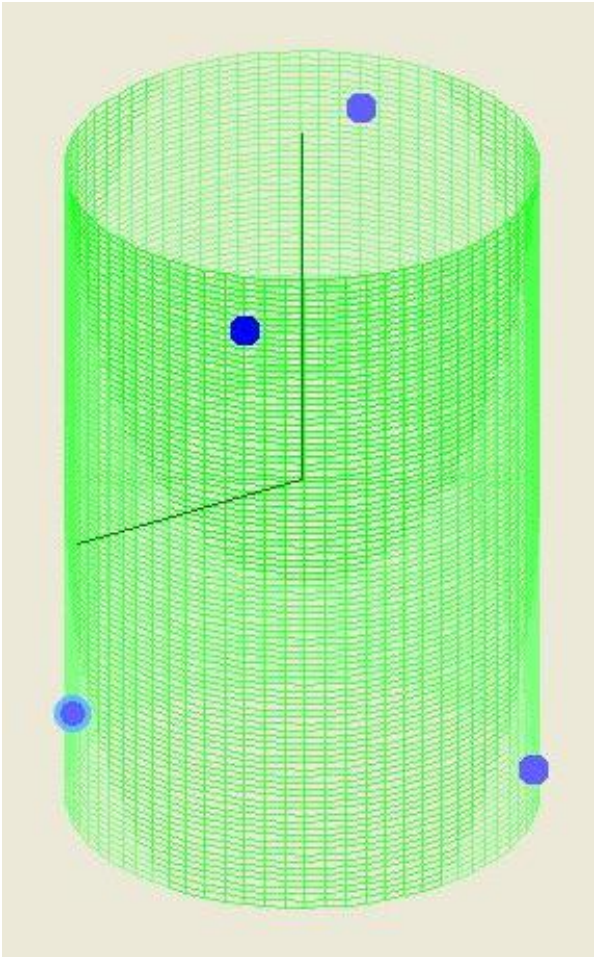
38212 in-lbs

Failed Tube

- Local buckling and delamination resulted in shear failure of the composite tube



Acoustic Emission Method

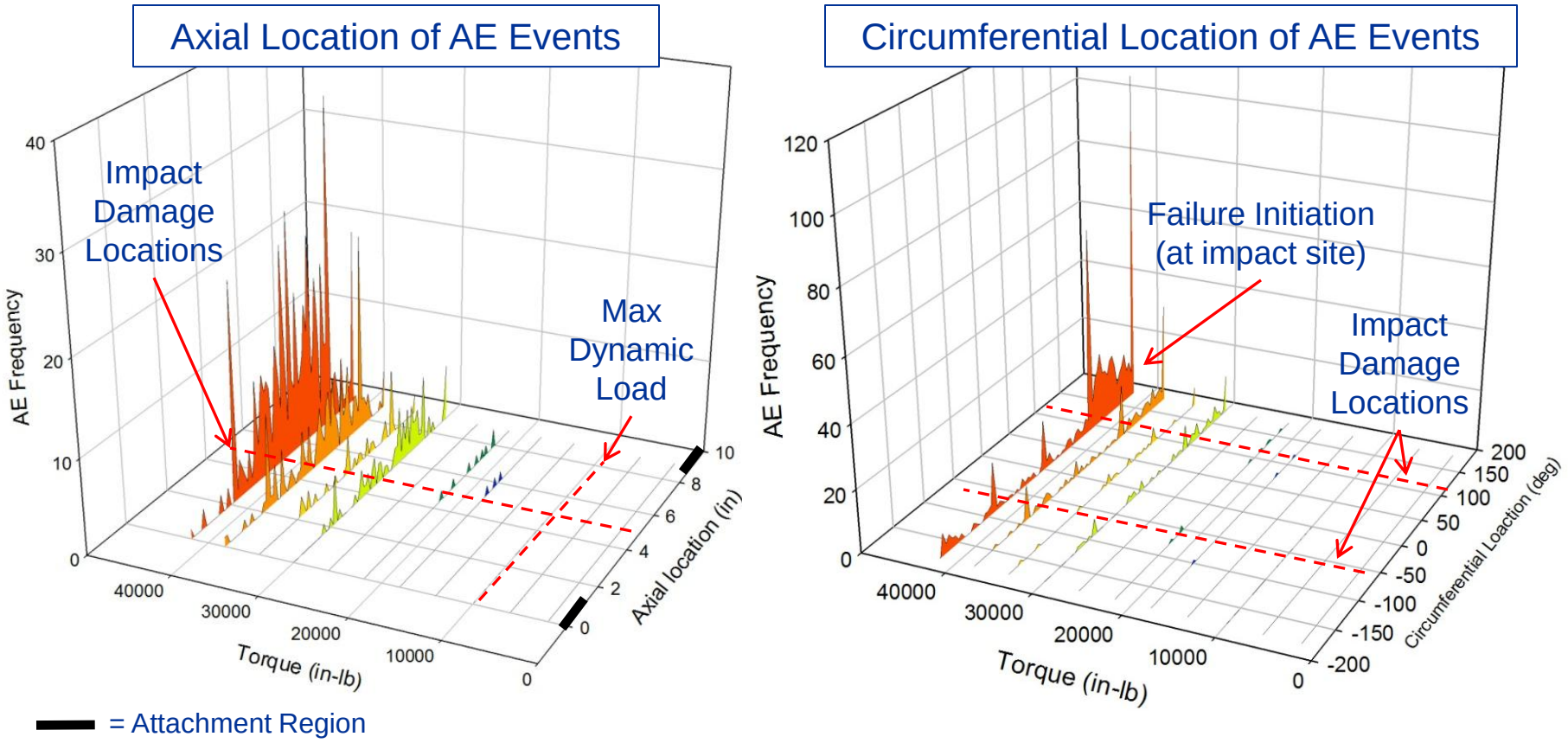


● = AE Sensor

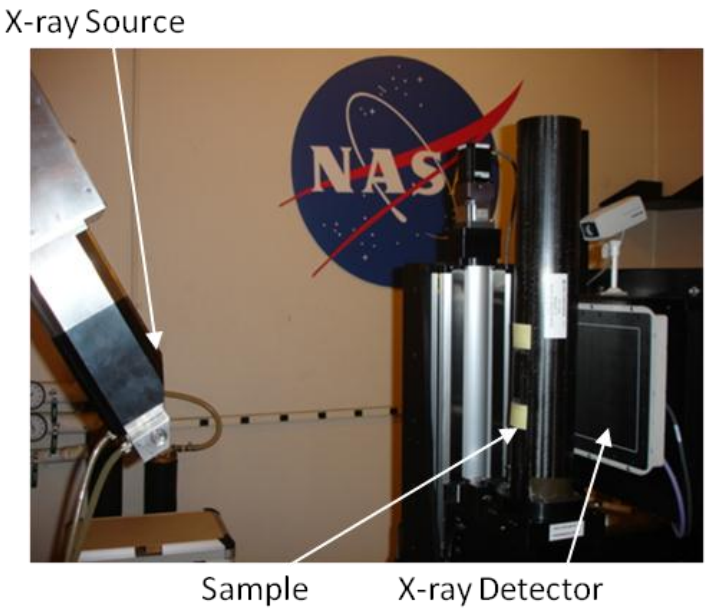
- 4 AE sensors mounted to tube
  - Broadband response (100kHz – 3MHz)
  - 90 degree increments
  - Alternating from top to bottom of unattached region
- Data collected continuously over entire loading and events correlated with applied load
- AE location identified based on arrival times, wave speed and known sensor locations.

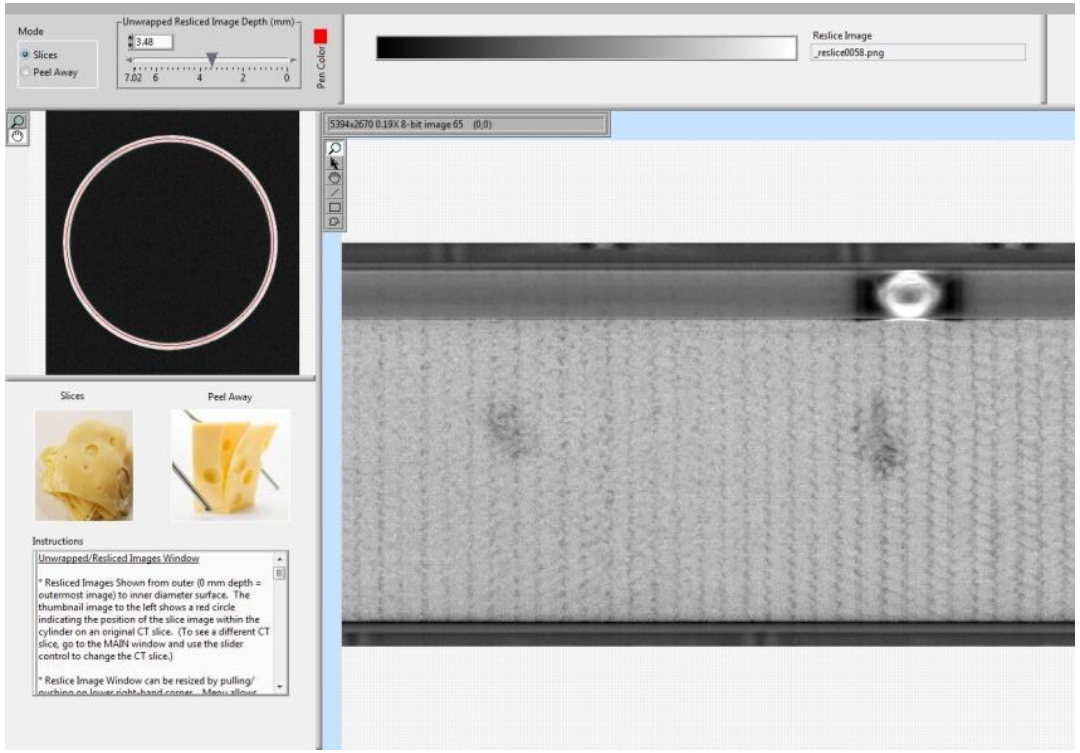
Acoustic Emission from Static Test

- Acoustic emission agrees with the development of additional damage at the impact damage locations
- Near higher loading, damage also occurs in attachment region



X-ray CT Cylindrical Unwrap Method

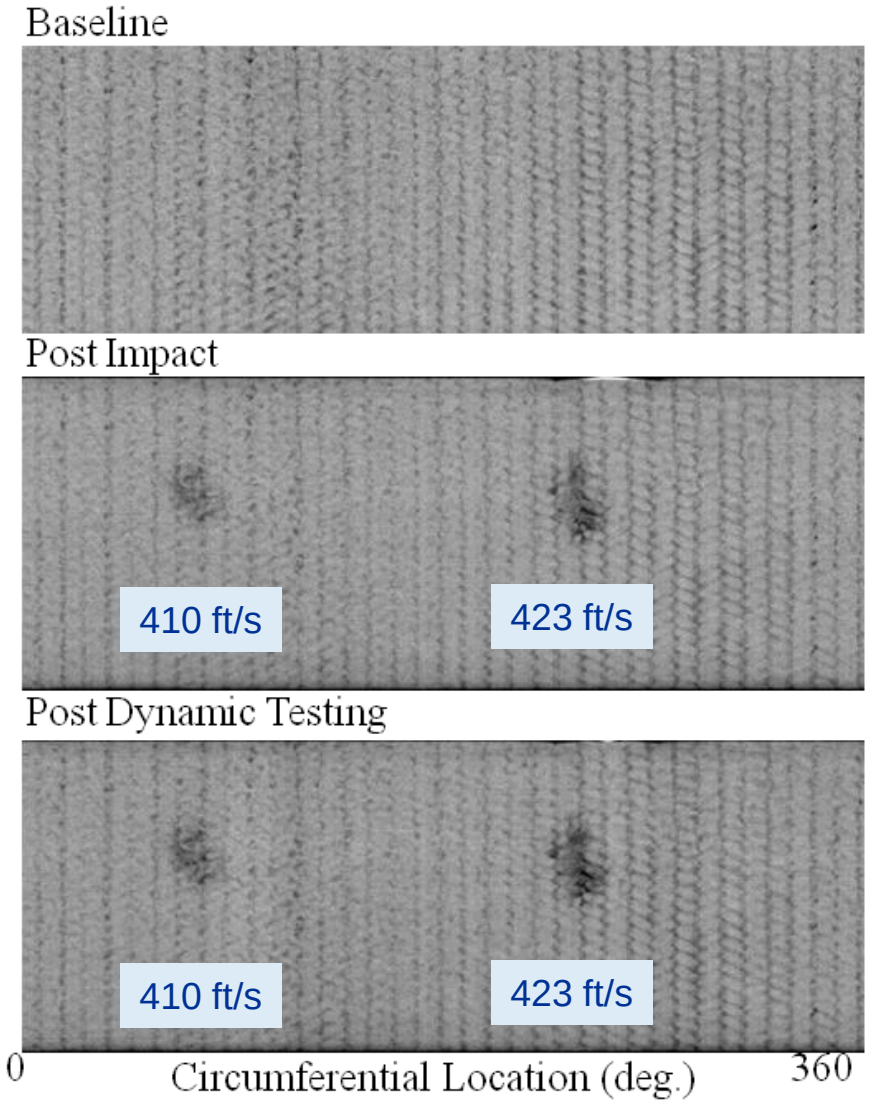




- Algorithms were used to unwrap the layers of the tube as circumferential slices
- Damage and/or defects in different plies within the composite can be observed

X-ray CT Observation of Damage

- No damage growth was observed following the dynamic test of the damaged tube
- Failure of the tube in the static test corresponded to the more severe damage observed by X-ray CT and higher impact velocity



Conclusions/Future Work

- The high speed DIC method was capable of resolving sufficient detail to indicate damage of the test article, though noise levels were high
- More light will reduce noise due to low camera signal and allow the exposure time to be shortened which will reduce error due to motion blur
- Pulsed lighting will be used to reduce heating of the test article
- A smaller field of view will be used to view local material damage
- Test articles with more complex geometry will be used in future tests

Thank you.

This work was supported by NASA's Rotary Wing Project.